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Abstract–This paper presents a robust control design procedure for induction motor drives in case of modeling errors and unknown load torque. The control law is based on the combination of nonlinear PI controllers and a backstepping methodology. More precisely, the controllers are determined by imposing flux-speed tracking in two steps and by using appropriate PI gains that are nonlinear functions of the system state. A comparative study between the proposed PI/Backstepping approach and the feedback linearizing control is made by realistic simulations including load torque changes, parameter variations and measurement noises. Flux-speed tracking results show the proposed method effectiveness in presence of strong disturbances.

Keywords: *Nonlinear PI control, backstepping, induction motor, robustness, flux-speed tracking, feedback linearizing control.*

I. Introduction

The development of induction motor drives has considerably accelerated in order to satisfy the increasing need of various industrial applications in low and medium power range. Indeed, induction motors have simple structure, high efficiency and increased torque/inertia ratio. However, their dynamical model is nonlinear, multivariable, coupled, and is subject to parameter uncertainties since the physical parameters are time-variant. The design of robust controllers becomes then a relevant challenge [1-2].

Induction motor drives control has been an active research domain over the last years. Different control techniques such as Field-Oriented control (FOC), feedback linearization control, sliding mode control passivity approach, and adaptive control have been reported in the literature [3]. The FOC ensures partial decoupling of the plant model using a suitable transformation and then PI controllers are used for tracking regulation errors. The high performance of such strategy may be deteriorated in practice due to plant uncertainties [4-5]. Exact input-output feedback linearization of induction motors model can be obtained using tools from differential geometry. This method cancels the nonlinear terms in the plant model which fails when the physical parameters varies [6-7]. By contrast, passivity-based control does not cancel all the nonlinearities but enforce them to be passive, i.e. dissipating energy and hence ensuring tracking regime [8-10]. Sliding Mode Control (SMC) is widely applied because of its easiness and attractive robustness properties [11-12]. On the other hand, SMC exhibits high-gain when the controlled system is subject to large parameter variations. This however limits the application of such control scheme. To overcome this problem, many authors have proposed sliding mode and adaptive control combined structure. This leads to reduced gain and robustness against matched and unmatched uncertainties [13-15]. Adaptive backstepping is also used for speed control to compensate the uncertainties that remains after input-output linearization [16-20]. Fuzzy logic and neural networks are also applied. Several control schemes have been developed. The main feature of such techniques is their intrinsic robustness properties as they do not require the plant model precise knowledge [21-24]. These approaches may introduce some time constraints in real-time applications.

Otherwise, the conventional PI controllers are the most common algorithms used in industry today. Their attractiveness is due to their structure simplicity and the industrial operators acquaintance with them. Several PI controllers have been proposed in the literature for linear and nonlinear processes [5], [25]. Nevertheless, PI controllers fundamental deficiency is the lack of asymptotic stability and robustness proofs for a given nonlinear system.

Therefore, this paper proposes to deal with this deficiency by proposing a robust nonlinear PI controller for an induction motor drive with unknown load torque. The controller is derived by combining a backstepping procedure with a PI structure. More precisely, the controllers are determined by imposing the current-speed tracking recursively in two steps and by using appropriate gains that are nonlinear functions of the system state.

II. Problem Formulation

2.1 Nomenclature

s, (r)	=	Stator (rotor) index;
α, β	=	Synchronous reference frame index;
ref	=	Reference index;
v (i)	=	Voltage (Current);
φ, ϕ	=	Flux;
Γ_r	=	Load torque;
R	=	Resistance;
L (M)	=	Inductance (Mutual inductance);
σ	=	Leakage coefficient;
T_s (T_r)	=	Stator (rotor) circuit time constant.
ω_r (ω_s)	=	Rotor speed (Synchronous speed);
k_f	=	Friction coefficient;
J	=	Rotor Inertia;
p	=	Pole pair number.

2.2 Induction Motor Model

In the stator reference frame, the state-space model of voltage-fed induction motor is derived from the Park model. The state vector is composed of the stator current components (i_α,i_β), rotor flux components (φ_α,φ_β) and rotor rotating pulsation ω_r, whereas a vector control is composed of the stator voltage components (v_α,v_β) and the external disturbance is represented by the load torque Γ_r [1], [3].

$$\begin{cases} x = \begin{pmatrix} x_1 & x_2 & x_3 & x_4 & x_5 \end{pmatrix}^{\mathrm{T}} = \begin{pmatrix} i_\alpha & i_\beta & \varphi_\alpha & \varphi_\beta & \omega_r \end{pmatrix}^{\mathrm{T}} \\ u = \begin{pmatrix} u_1 & u_2 \end{pmatrix}^{\mathrm{T}} = \begin{pmatrix} v_\alpha & v_\beta \end{pmatrix}^{\mathrm{T}} \end{cases}$$

Using these notations, the state-space model of a voltage-fed induction motor should be written as

$$\begin{cases} \dot{x}_1 = f_1(x) + d_1 u_1, & f_1(x) = -a_1 x_1 + b_1 x_3 + c_1 x_4 x_5 \\ \dot{x}_2 = f_2(x) + d_1 u_2, & f_2(x) = -a_1 x_2 + b_1 x_4 - c_1 x_3 x_5 \\ \dot{x}_3 = f_3(x), & f_3(x) = a_3 x_1 - b_3 x_3 - x_4 x_5 \\ \dot{x}_4 = f_4(x), & f_4(x) = a_3 x_2 - b_3 x_4 + x_3 x_5 \\ \dot{x}_5 = f_5(x), & f_5(x) = -a_5 x_5 - b_5 x_1 x_4 + b_5 x_2 x_3 - c_5 \Gamma_r \end{cases} \tag{1}$$

The coefficients (a_1 ,..., c_5) are given by

$$\begin{cases} a_1 = \dfrac{1}{\sigma T_s} + \dfrac{1-\sigma}{\sigma T_r},\ a_3 = \dfrac{M}{T_r},\ a_5 = \dfrac{k_f}{J} \\ b_1 = \dfrac{(1-\sigma)}{\sigma M T_r},\ b_3 = \dfrac{1}{T_r},\ b_5 = p^2 \dfrac{M}{J L_r} \\ c_1 = \dfrac{(1-\sigma)}{\sigma M},\ c_5 = p \dfrac{1}{J} \\ d_1 = \dfrac{1}{\sigma L_s} \\ \sigma = 1 - \dfrac{M^2}{L_s L_r},\ T_s = \dfrac{R_s}{L_s},\ T_s = \dfrac{R_r}{L_r} \end{cases}$$

2.3 Control Objectives

Our objective is to control the rotor speed ω_r and the rotor flux magnitude $\phi = x_3^2 + x_4^2$ using nonlinear PI controllers. For that purpose, let $e_1 = \phi - \phi_{ref}$ and $e_2 = \omega - \omega_{ref}$. The error dynamics are then as follows.

$$\begin{cases} \dot{e}_1 = -2 b_3 \phi - \dot{\phi}_{ref} + 2 a_3 \xi_1 \\ \dot{e}_2 = -a_5 x_5 - c_5 \Gamma_r - \dot{\omega}_{ref} + b_5 \xi_2 \end{cases} \tag{2}$$

where
$$\begin{cases} \xi_1 = x_3 x_1 + x_4 x_2 \\ \dot{\xi}_1 = f_{\xi 1}(x) + d_1 x_3 u_1 + d_1 x_4 u_2 \\ \xi_2 = x_3 x_2 - x_4 x_1 \\ \dot{\xi}_2 = f_{\xi 2}(x) - d_1 x_4 u_1 + d_1 x_3 u_2 \end{cases}$$

and
$$\begin{cases} f_{\xi 1}(x) = x_3 f_1 + x_4 f_2 + x_1 f_3 + x_2 f_4 \\ f_{\xi 2}(x) = x_2 f_3 + x_3 f_2 - x_4 f_1 - x_1 f_4 \end{cases}$$

It can be seen that:

i. The flux tracking error e_1 can be controlled using the auxiliary variable ξ_1.

ii. The speed tracking error e_2 can be controlled using the auxiliary variable ξ_2.

iii. The auxiliary variables (ξ_1,ξ_2) can be controlled using the real control signal $u = (u_1\ u_2)^{\mathrm{T}}$.

Let ξ_2^d be the value of ξ_2 ensuring the stabilization of the sped-tracking error e_2. This desired value is determined using Lyapunov approach by considering the dynamic equation of e_2. Also, let ξ_1^d be the value of ξ_1 ensuring convergence of the flux-tracking error e_1. Thereafter, the control objective becomes: force the auxiliary variable ξ_1 to track ξ_1^d while ξ_2 must track ξ_2^d. Hence, let $e_3 = \xi_1 - \xi_1^d$ and $e_4 = \xi_2 - \xi_2^d$ define $E = (e_3\ e_4)^{\mathrm{T}}$. The proposed control signal is then

$$u(t) = \begin{pmatrix} u_1(t) \\ u_2(t) \end{pmatrix} = K_p(x) E(t) + K_i(x) \int_0^t E(\tau) d\tau \tag{3}$$

Equation (3) defines a multivariable nonlinear PI controller for which the proportional gain K_p (respectively the integral gain K_i) is a 2×2 matrix whose elements nonlinearly depend on the induction motor state vector.

A backstepping methodology is used to design the control gains ensuring the outputs tracking [16-20].

<u>Step 1</u>: Search of the virtual control $\xi_1^d(t)$ that ensure the asymptotic convergence of the flux-tracking error $e_1(t)$ to zero. Then, search of the virtual control $\xi_2^d(t)$ that guarantees the asymptotic convergence of the speed-tracking error $e_2(t)$ to zero.

<u>Step 2</u>: Using an augmented Lyapunov function, determination of the multivariable PI gain

matrices K_p and K_i that force the errors $e_3 = \xi_1 - \xi_1^d$ and $e_4 = \xi_2 - \xi_2^d$ to converge to zero leading to flux (e_1) and speed (e_2) tracking errors exponential convergence.

III. Nonlinear PI-Based Backstepping Control Design

Let us first derive the auxiliary variables ensuring flux-speed tracking. One has the following result.

Proposition 1: Consider the dynamic (2). Then flux and speed tracking errors $e_1(t)$ and $e_2(t)$ are exponentially stable provided that

$$\begin{cases} \xi_1^d(t) = \dfrac{1}{a_3}\left[b_3\phi + \dfrac{1}{2}\dot{\phi}_{ref} - \lambda_1 e_1(t)\right] \\ \xi_2^d(t) = \dfrac{1}{b_5}\left[a_5 x_5 - \lambda_3 sign(e_2) + \dot{\omega}_{ref} - \lambda_2 e_2(t)\right] \\ \lambda_3 > \left|c_5 \Gamma_r\right| \end{cases} \tag{4}$$

Proof: Consider the following Lyapunov function related to the flux dynamic defined in (2).

$$V_1 = \frac{1}{2}e_1^2(t) + \frac{1}{2}e_2^2(t) \tag{5}$$

Its time-derivative is expressed by

$$\dot{V}_1 = e_1(t)\dot{e}_1(t) + e_2(t)\dot{e}_2(t) \tag{6}$$

If the virtual control laws ξ_1 and ξ_2 are forced to take the desired value given by (4), the Lyapunov function time-derivative takes the following final form.

$$\dot{V}_1 \leq -\lambda_1 e_1^2 - \lambda_1 e_2^2 \tag{7}$$

Provided that $\lambda_3 > \left|c_5 \Gamma_r\right|$ (8)

It implies that e_1 and e_2 are exponentially stable.

End of Proof

Remark 1: Even if the load Γ_r torque is unknown, one can always ensure speed-tracking due to (8). Moreover, (8) can also cope with modeling errors and parametric variations in the speed dynamical equation.

The real control signal $u = (u_1 \ u_2)^T$, that force the errors $e_3 = \xi_1 - \xi_1^d$ and $e_4 = \xi_2 - \xi_2^d$ to converge to zero, will be now derived. One needs the following definitions: Consider a real nonlinear function $S(x)$ satisfying $xS(x) > 0 \ \forall \ x \neq 0$. Examples of such functions are $S(x) = x^{2k+1}$ (k positive integer), or $S(x) = \sinh(x)$, or $S(x) = \tanh(x)$, or $S(x) = \mathrm{sign}(x)$.

Let $K_p(x) = -A^{-1}(x)\begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix} = -A^{-1}(x)K$ (9)

with K any positive definite matrix.

$$K_i(x) = -A^{-1}(x)\{\Gamma\} \tag{10}$$

Where

$$\begin{cases} A(x) = \begin{bmatrix} d_1 x_3 & d_1 x_4 \\ -d_1 x_4 & d_1 x_3 \end{bmatrix} \\ \Gamma = \begin{bmatrix} \gamma_1 S(z_1) & 0 \\ 0 & \gamma_2 S(z_2) \end{bmatrix}, \ z_i = e_{i+2}\displaystyle\int_0^t e_{i+2}(\tau)d\tau, \text{ for } i = 1, 2 \end{cases} \tag{11}$$

One has the following result.

Proposition 2: Consider the induction motor dynamic (1) in closed-loop with the multivariable PI control (3), (9-1&). Assume that the gains γ_1 and γ_2 are such that

$$\begin{cases} \left|\gamma_1 S(z_1)\displaystyle\int_0^t e_3\right| > \bar{F}_1 \text{ with } \bar{F}_1 \geq 2a_3\left|e_1\right| + \left|f_{\xi 1} - \dot{\xi}_1^d\right| \\ \left|\gamma_2 S(z_2)\displaystyle\int_0^t e_4\right| > \bar{F}_2 \text{ with } \bar{F}_2 \geq b_5\left|e_2\right| + \left|f_{\xi 2} - \dot{\xi}_2^d\right| \end{cases} \tag{12}$$

Then, the following properties are verified.

i. The tracking errors $e_1(t)$, $e_2(t)$, $e_3(t)$, and $e_4(t)$ are exponentially stable.

ii. The closed-loop system is internally stable.

Proof: Consider the augmented Lyapunov function.

$$V_2 = V_1 + \frac{1}{2}E^T E \tag{13}$$

Its time derivative is given by

$$\dot{V}_2 = \dot{V}_1 + E^T \dot{E} \tag{14}$$

Recalling that $\dot{V}_1 = -\lambda_1 e_1^2 - \lambda_2 e_2^2 + 2a_3 e_1 e_3 + b_5 e_2 e_4$

this gives $\dot{V}_2 \leq -\lambda_1 e_1^2 - \lambda_2 e_2^2 + E^T\left[\dot{E} + \begin{pmatrix} 2a_3 e_1 \\ b_5 e_2 \end{pmatrix}\right]$ (15)

Replacing the dynamics of E by

$\dot{E} = \begin{pmatrix} f_{\xi 1} - \dot{\xi}_1^d \\ f_{\xi 2} - \dot{\xi}_2^d \end{pmatrix} + A(x)u$ and the control signal by (3)

then one have

$$\dot{V}_2 \le -\lambda_1 e_1^2 - \lambda_2 e_2^2 - E^T K E + v(t) \tag{16}$$

where $v(t) = E^T \left[\begin{pmatrix} 2a_3 e_1 \\ b_5 e_2 \end{pmatrix} + \begin{pmatrix} f_{\xi 1} - \dot{\xi}_1^d \\ f_{\xi 2} - \dot{\xi}_2^d \end{pmatrix} - \Gamma \int_0^t E d\tau \right]$

If $v(t) < 0$ then

$$\dot{V}_2 < -\lambda_1 e_1^2 - \lambda_2 e_2^2 - E^T K E < 0 \ \forall e_i \ne 0 \text{ for } i = 1,2,3,4$$

In this case, one concludes that property *i* is verified. Notice that

$$v(t) = E^T \left[\begin{pmatrix} 2a_3 e_1 \\ b_5 e_2 \end{pmatrix} + \begin{pmatrix} f_{\xi 1} - \dot{\xi}_1^d \\ f_{\xi 2} - \dot{\xi}_2^d \end{pmatrix} \right] - \begin{bmatrix} \gamma_1 z_1 S(z_1) \\ \gamma_2 z_2 S(z_2) \end{bmatrix} \tag{17}$$

Since the terms $z_i S(z_i)$; I = 1, 2, are always positive, $v(t)$ is negative provided the gains γ_I and γ_2 are such that inequalities (12) are satisfied.

The convergence of the output tracking error e_i (i = 1, 2, 3, 4) to zero does not implies that the state vector $x = [x_1\ x_2\ x_3\ x_4]^T$ of the induction motor remains bounded. However, since $e_2 = x_5 - \omega_{ref}$ and $e_1 = x_3^2 + x_4^2 + \phi_{ref}$ are exponentially stable with ω_{ref} and ϕ_{ref} bounded. Therefore, one concludes that the states x_3, x_4 and x_5 are all-time bounded. Let $\beta = (x_1\ x_2)^T$ and $\eta = (x_3\ x_4\ x_5)^T$. The state η has already been proven to be bounded. From (1), it can be seen that since a_1 is positive, the origin of the subsystem $\dot{\beta} = f(\beta, \eta_d)$ is stable for any fixed value η_d of the vector η. One can therefore conclude that the state β is bounded. **End of Proof**

Remark 2: In order to compute the boundaries $\bar{F}_i$, load torque and functions f_i exact knowledge is not needed. Bounds can be used on these variables. In this case, the proposed control law is still valid in presence of parametric uncertainties that corrupt the system dynamics.

Remark 3: The PI gains developed in proposition 2 are nonlinear and may be time-variant. Further, the integral gains must be sufficiently large to fulfill constraints (12). The proportional gains define the slope of the closed-loop system dynamics and they may be time-variant.

IV. Comparative Study

In this section, a comparison is carried-out between the proposed PI/Backstepping control approach with the well-known feedback linearizing control (FLC), which is generally used for decoupling and linearizing nonlinear systems [6-7]. In brief, the induction motor model is written in the following form.

$$\begin{cases} \dot{X} = f(X) + g_1(X)u_1 + g_2(X)u_2 \\ y_1 = h_1(X) \\ y_2 = h_2(X) \end{cases} \tag{18}$$

Then, the output variables are differentiated with respect to time until at least one of the inputs appears. This can be easily done by using the Lie derivative of a state function $h(X)$ along a vector field $f(X)$ defined by

$$L_f h(X) = \sum \frac{\partial h(X)}{\partial x_i} f_i(X) \tag{19}$$

Considering the induction motor model (1) and using the approach developed in [7], the resulting control signal ensuring feedback linearization is given by

$$\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} 2a_3 d_1 x_3 & 2a_3 d_1 x_4 \\ -b_5 d_1 x_4 & b_5 d_1 x_3 \end{bmatrix}^{-1} \begin{bmatrix} 2b_3 \dot{\phi} - 2a_3 f_{\xi 1} + v_1 \\ -b_5 f_{\xi 2} + a_5 \dot{x}_5 + v_2 \end{bmatrix} \tag{20}$$

where $v = \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} -k_1 e_1 - k_2 \dot{e}_1 + \ddot{\phi}_{ref} \\ -k_3 e_2 - k_4 \dot{e}_2 + \ddot{\omega}_{ref} \end{bmatrix}$ (21)

is an auxiliary control signal used to stabilize the resulting linear system. The gains k_i are designed by pole placement of the error dynamics. Notice that this method cancels the nonlinear terms in the plant model.

The simulated induction motor ratings are given in the Appendix.

The PI gains are chosen as indicated in Proposition 2. They are adjusted till satisfactory results are obtained. $S(z)$ functions are taken as follows

$$S(z) = \begin{cases} sign(z) & \text{if } |z| > \varepsilon \\ \dfrac{z}{\varepsilon} & \text{if } |z| \le \varepsilon \end{cases} \tag{22}$$

with ε = 0.01. The following PI gains have been used for all the simulated situations.

$$\begin{cases} k_1^p = 500 \\ k_2^p = 500 \\ k_1^i = 40000 \\ k_2^i = 800 \end{cases}$$

For the feedback linearization control simulations, the gains are chosen as follows.

$$\begin{cases} k_1 = 100 \\ k_2 = 20 \\ k_3 = 49 \\ k_4 = 14 \end{cases}$$

To test the proposed PI/Backstepping control approach, three typical situations have been simulated.

4.1 Test 1 – Ideal Case

Speed and flux tracking are checked for no load torque and no parameter variations case. Simulation results are illustrated by Figs. 1 and 2 for PI/Backstepping control and feedback linearizing control, respectively. It can be noticed that both control approaches ensure good current and speed tracking. However, the feedback linearizing control is advantageous since it allows decoupling between flux and speed dynamics, which is not the case of the proposed approach.

4.2 Test 2 – Unknown Load Torque

Speed and flux tracking are now checked in the case of an unknown load torque ($\Gamma_r = 3\Gamma_{nom}$) applied between t = 2sec and t = 4sec. The control performances are illustrated by Figs. 3 and 4. It can be noticed that feedback linearizing control fails to guarantee speed tracking. Conversely, PI/Backstepping control still guarantees it. This result is very interesting since in practice the load torque is unknown and time-variant.

4.3 Test 3 – Parameter Variations

For the PI/Backstepping control approach, simulations have been carried-out with 50% variation in all the parameters of (1) starting from t = 2sec till t = 4sec. The obtained results are very satisfactory and show strong robustness against parameter variations (Fig. 5).

In the same above simulation conditions, an unstable feedback loop is achieved for feedback linearizing control. For illustration, parameters a_5 and b_5 are varied and all the others are maintained constant. Even in this case, decoupling between speed and flux dynamics is lost and further speed tracking is very poor (Fig. 6).

V. Conclusion

This paper has presented a robust control design procedure for induction motor drives in case of modeling errors and unknown load torque. The control law is based on the combination of nonlinear PI controllers and a backstepping approach. More precisely, the controllers are determined by imposing flux-speed tracking in two steps and by using appropriate PI gains that are nonlinear functions of the system state.

A comparative study between the proposed PI/Backstepping approach and the feedback linearizing control is made by realistic simulations including load torque changes, parameter variations and measurement noises. Flux-speed tracking results show the proposed control approach effectiveness in presence of strong disturbances.

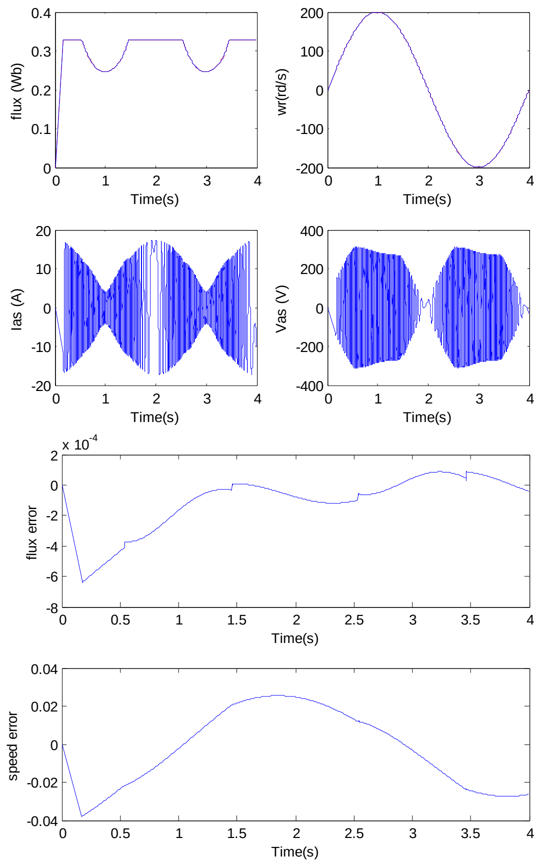

Fig. 1. PI/Backstepping control: Test 1.

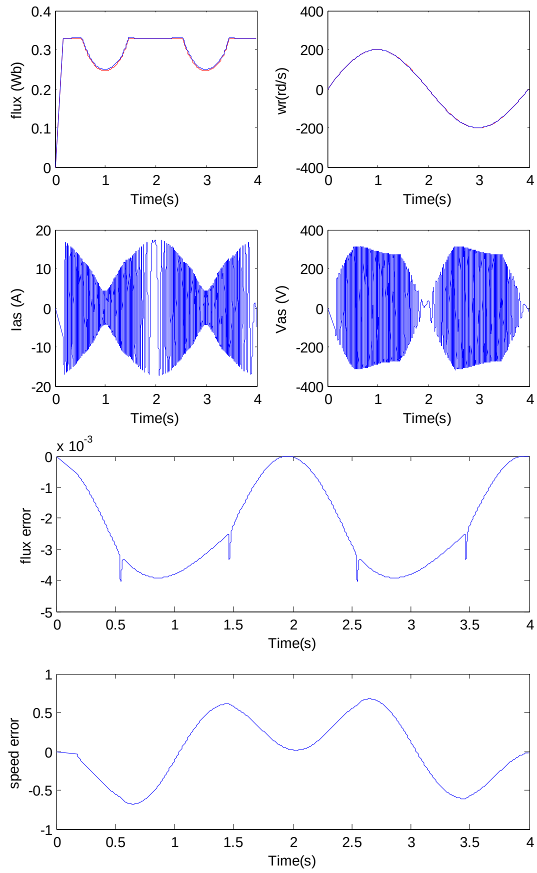

Fig. 2. Feedback linearizing control: Test 1.

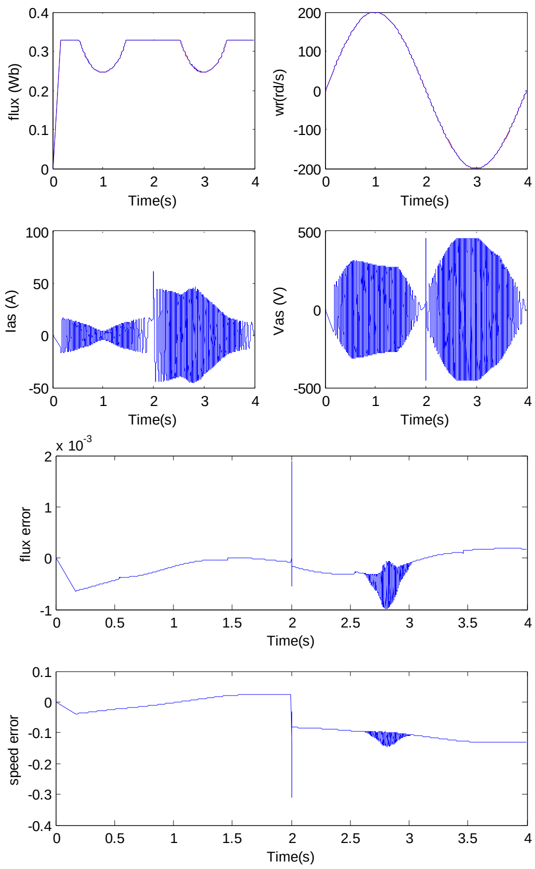

Fig. 3. PI/Backstepping control: Test 2.

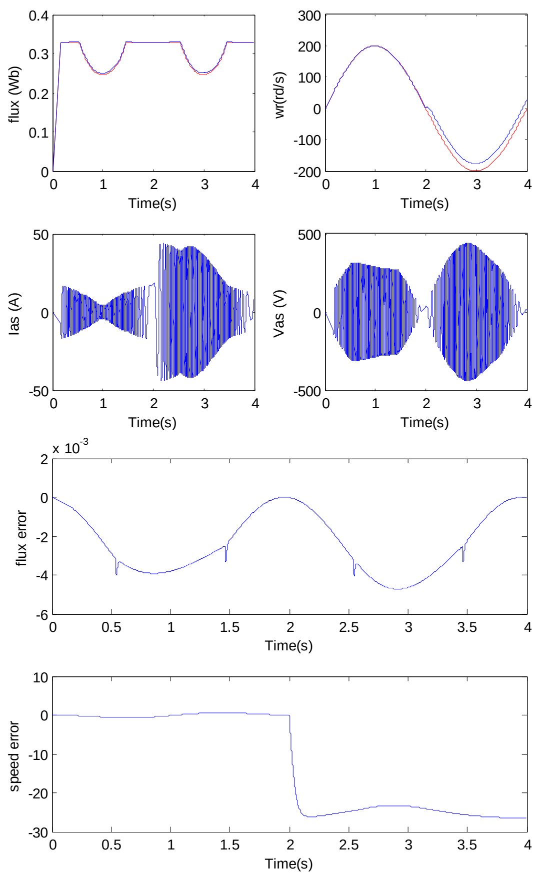

Fig. 4. Feedback linearizing control: Test 2.

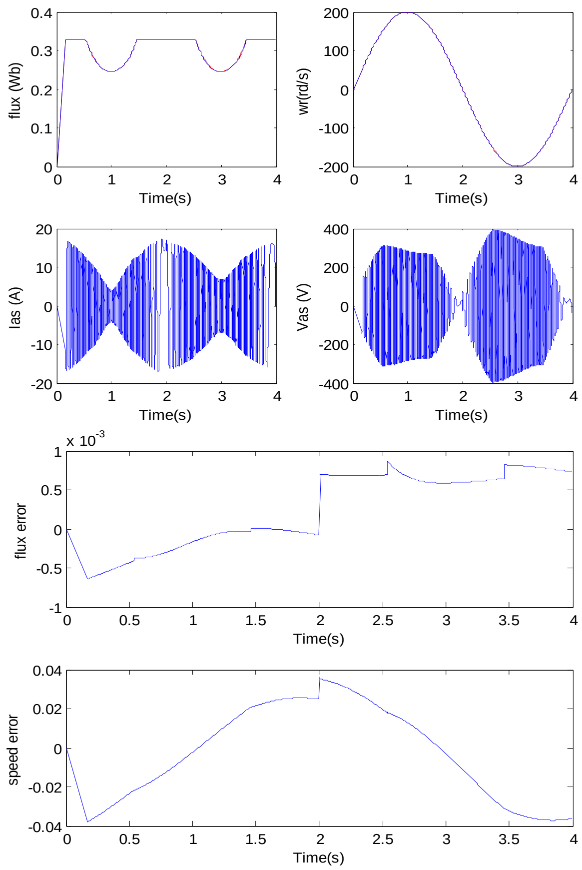

Fig. 5. PI/Backstepping: Test 3.

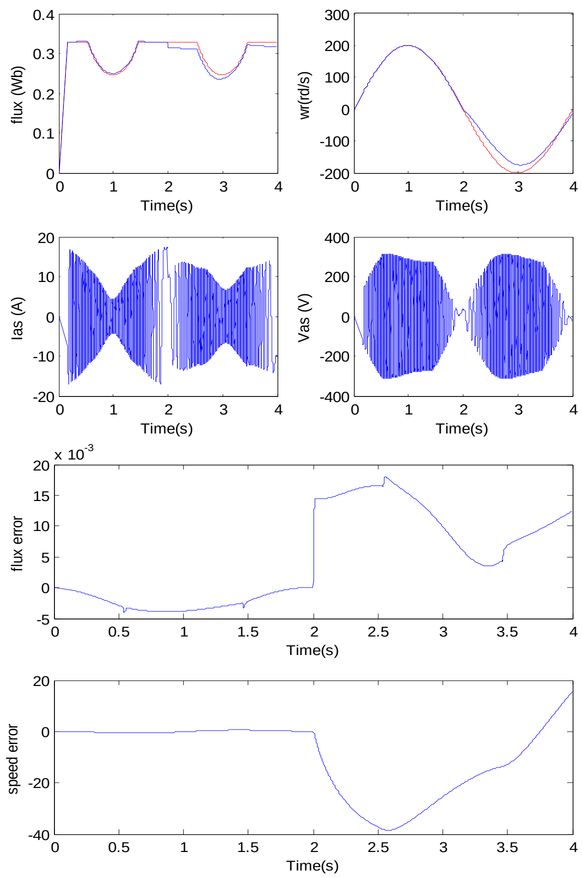

Fig. 6. Feedback linearizing control: Test 3.

Appendix

Rated Data of the Simulated Induction Motor

4 kW, 23.8 Nm, 1500 rpm, $p = 2$
$R_s = 1.125\ \Omega$, $R_r = 1.103\ \Omega$, $L_s = 0.17$ H, $L_r = 0.015$ H, $M = 0.048$ H
$J = 0.135$ kg.m², $k_f = 0.00182$ Nm.s

References

[1] P.C. Krause et *al*. *Analysis of Electric Machinery and Drive Systems*. John Wiley & Sons: 2002.

[2] P.V. Kokotovic et *al*. *Nonlinear and Adaptive control*. John Wiley & Sons: 1995.

[3] Leonhard W. *Control of Electrical Drives*. Springer-Verlag, 1996.

[4] A. Behal et *al*., "An improved IFOC for the induction motor," *IEEE Trans. Control Systems Technology*, vol. 11, n°2, pp. 248-252, March 2003.

[5] D. Casadei et *al*., "FOC and DTC: two viable schemes for induction motors torque control," *IEEE Trans. Power Electronics*, vol. 17, n°5, pp. 779-787, September 2002.

[6] J. Chiasson, "A new approach to dynamic feedback linearization control of an induction motor," *IEEE Trans. Automatic Control*, vol. 42, n°3, pp. 391-397, March 1998.

[7] R. Marino et *al*., "Adaptive input-output linearizing control of induction motors," *IEEE Tran. Automatic Control*, vol. 38, n°2, pp. 208-221, February 1993.

[8] G.W. Chang et *al*., "Tuning rules for the PI gains of field-oriented controllers of induction motors," *IEEE Trans. Industrial Electronics*, vol. 47, n°3, pp. 592-602, June 2000.

[9] C. Cecati et *al*., "Torque and speed regulation of induction motors using passivity theory approach," *IEEE Tran. Industrial Electronics*, vol. 46, n°1, pp. 23-36. February 1999.

[10] P.J. Nicklasson et *al*., "Passivity-based control of a class of Blondel-Park transformable electric machines," *IEEE Tran. Automatic Control*, vol. 42, n°5, pp. 629-647. May 1997.

[11] M. Comanescu et *al*., "Decoupled current control of sensorless induction-motor drives by integral sliding mode," *IEEE Trans. Industrial Electronics*, vol. 55, n°11, pp. 3836-3845, November 2008.

[12] A. Derdiyok, "Speed-sensorless control of induction motor using a continuous control approach of sliding-mode and flux observer," *IEEE Trans. Industrial Electronics*, vol. 52, n°4, pp. 1170-1176, August 2005.

[13] S. Hasan et *al*., "A Luenberger–Sliding mode observer for online parameter estimation and adaptation in high-performance induction motor drives," *IEEE Trans. Industry Applications*, vol. 45, n°2, pp. 772-781, March-April 2009.

[14] D. Traore et *al*., "Sensorless induction motor: High-order sliding-mode controller and adaptive interconnected observer," *IEEE Trans. Industrial Electronics*, vol. 55, n°11, pp. 3818-3827, November 2008.

[15] M. Comanescu et *al*., "Sliding-mode MRAS speed estimators for sensorless vector control of induction machine," *IEEE Trans. Industrial Electronics*, vol. 53, n°1, pp. 146-153, February 2006.

[16] A. Abbou et *al*., "Design of a new sensorless controller of induction motor using backstepping approach," *International Review of Electrical Engineering*, vol. 4. n°3, pp. 174-181, February 2008.

[17] S. Chaouch et *al*., "Backstepping control design of sensorless speed induction motor based on MRAS technique," *International Review of Electrical Engineering*, vol. 2. n°1, pp. 738-744, October 2007.

[18] M. Tadjine et *al*., "Robust backstepping vector control for the doubly fed induction motor," *IET Control Theory & Applications*, vol. 1, n°4, pp. 861-868, July 2007.

[19] A. Ebrahim et *al*., "Adaptive backstepping control of an induction motor under time-varying load torque and rotor resistance uncertainty," *In Proceedings of the IEEE SSST'06*, Cookville, (USA), pp. 512-518, March 2006.

[20] H. Tan et *al*., "Adaptive backstepping control of induction motor with uncertainties," *In Proceedings of the IEEE ACC'99*, San Diago (USA), vol. 1, pp. 1-5, June 1999.

[21] M.E.H. Benbouzid et *al*., "Direct torque control of induction motor with fuzzy stator resistance adaptation," *IEEE Trans. Energy Conversion*, vol. 21, n°2, pp. 619-621, June 2006.

[22] M. Masiala et *al*., "Fuzzy self-tuning speed control of an indirect field-oriented control induction motor drive, *IEEE Trans. Industry Applications*, vol. 44, n°6, pp. 1732-1740, November-December 2008.

[23] M.E.H. Benbouzid et *al*., "Modeling, analysis, and neural network control of an EV electrical differential," *IEEE Trans. Industrial Electronics*, vol. 55, n°6, pp. 2286-2294, June 2008.

[24] L. Barazane et *al*., "Optimization by gaussian radial basis function neural network of the performance of induction motor system based on new linguistic fuzzy model," *International Review of Electrical Engineering*, vol. 3. n°2, pp. 344-354, April 2008.

[25] I. Boldea et *al*. *Vector Control of AC Drives*. CRC Press: 1992.

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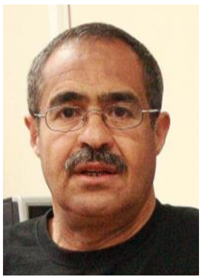

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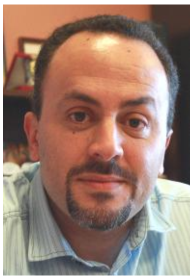

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